

## STAR FORMATION AND YOUNG POPULATION OF THE H II COMPLEX SH2-294

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## ABSTRACT

The Sh2-294 H II region ionized by a single B0V star features several infrared excess sources, a photodissociation region, and also a group of reddened stars at its border. The star formation scenario in the region seems to be quite complex. In this paper, we present follow-up results of Sh2-294 H II region at 3.6, 4.5, 5.8, and 8.0  $\mu\text{m}$  observed with the *Spitzer Space Telescope* Infrared Array Camera (IRAC), coupled with H<sub>2</sub> (2.12  $\mu\text{m}$ ) observation, to characterize the young population of the region and to understand its star formation history. We identified 36 young stellar object (YSO, Class I, Class II and Class I/II) candidates using IRAC color-color diagrams. It is found that Class I sources are preferentially located at the outskirts of the H II region and associated with enhanced H<sub>2</sub> emission; none of them are located near the central cluster. Combining the optical to mid-infrared (MIR) photometry of the YSO candidates and using the spectral energy distribution fitting models, we constrained stellar parameters and the evolutionary status of 33 YSO candidates. Most of them are interpreted by the model as low-mass ( $<4 M_{\odot}$ ) YSOs; however, we also detected a massive YSO ( $\sim 9 M_{\odot}$ ) of Class I nature, embedded in a cloud of visual extinction of  $\sim 24$  mag. Present analysis suggests that the Class I sources are indeed younger population of the region relative to Class II sources (age  $\sim 4.5 \times 10^6$  yr). We suggest that the majority of the Class I sources, including the massive YSOs, are second-generation stars of the region whose formation is possibly induced by the expansion of the H II region powered by a  $\sim 4 \times 10^6$  yr B0 main-sequence star.

*Subject headings:* stars: formation – stars: pre-main-sequence – ISM: H II regions – ISM: individual objects: Sh2-294

## 1. INTRODUCTION

The massive OB stars have profound influence on the evolution of molecular clouds and consequently influence star formation. The stellar radiation and winds due to massive stars in the region can sweep low density interstellar matter, consequently forming a dense layer of gas at the periphery of H II regions or they can compress existing primordial clumps. In both the processes, the matter at the later stage becomes unstable against self gravity to form young protostars. These two are commonly known processes that can induce new generation of star formation around expanding H II regions (see e.g., Sugitani et al. 2002; Deharveng et al. 2005; Chauhan et al. 2009; Samal et al. 2010; Ojha et al. 2011). Sh2-294 ( $\alpha_{2000} = 07^{\text{h}}16^{\text{m}}34.5^{\text{s}}$ ,  $\delta_{2000} = -09^{\circ}26'38''$ ) is an H II region powered by a B0V star and is possibly interacting with a molecular cloud, thus creating a photon dominated region (PDR) which can be seen towards the eastern side as polycyclic aromatic hydrocarbon (PAH) emission in MSX A-band (Samal et al. 2007; Paper-I). Using multiwavelength observations, Samal et al. (2007) have studied the stellar content, distribution of ionized, and dust emission in the region. They identified two groups of stars, one of which is associated with the B0V

star at the center of the optically visible nebula. The second group (termed as “region A”) is situated at the eastern side of the optical cluster and near the peak of 8  $\mu\text{m}$  emission along the PDR. Samal et al. (2007), using the optical colour-magnitude diagram and theoretical evolutionary models, estimated the age of the ionizing source as  $4 \times 10^6$  yr, whereas low mass pre-main-sequence (PMS) stars show an age spread of  $1\text{--}5 \times 10^6$  yr. On the basis of youth of the sources in “region A” (age  $\leq 1 \times 10^6$  yr) compared to the age of the ionizing source ( $\sim 4 \times 10^6$  yr), Samal et al. (2007) suggested Sh2-294 as a site of triggered star formation. However, the mechanism that is responsible for the initiation of new star formation in this region is still not clearly understood; requires proper identification and characterization of stellar sources present in the region to put a step ahead. On the basis of high resolution near-infrared (NIR) and optical observations, Yun et al. (2008) estimated the age of the ionizing source of Sh2-294 as  $4 \times 10^6$  yr, but suggested a higher age for the PMS sources. Due to the absence of spectroscopic or longer wavelength ( $\lambda > 2.2 \mu\text{m}$ ) observations, the exact nature and evolutionary status of the PMS sources in the region could not be studied so far. Now with high angular resolution of *Spitzer Space Telescope* it is possible to make a more reliable membership census of the young stellar objects with disk and envelope of the region, as 3–8  $\mu\text{m}$  bands of *Spitzer* reduce the degeneracy between selective interstellar extinction and intrinsic IR excess. Moreover, the nature of YSOs can be best accomplished using their broadband SEDs and its comparison with more sophisticated radiative transfer SED fitting models (e.g., Robitaille et al. 2007). Thus, in conjugation with the available photometric data sets

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for the region, the *Spitzer* observations will allow us to characterize the individual YSOs with their SEDs and constrained their evolutionary status, thus will help to establish spatial and temporal relationship among the YSOs. Therefore, we revisited the region at near- and mid-infrared windows for the follow up study of Sh2-294 star-forming-region (SFR), to have a better picture of star formation activity. The distance to Sh2-294 is uncertain and varies from 3.2 kpc to 4.8 kpc (Moffat et al. 1979; Samal et al. 2007; Yun et al. 2008). In this work, we adopted an average distance of 4.0 kpc for our analysis and organized the paper with the following layout. We describe the *Spitzer* observations and data reduction techniques in §2. In §3, the observational results are presented, which includes morphology of the region, identification of the YSOs and their properties obtained with SED modelling. The star formation scenario in the region is discussed in §4 and §5 summarizes our results.

## 2. OBSERVATIONS AND DATA REDUCTION

The archived MIR data for the region were obtained with the Infrared Array Camera (IRAC; Fazio et al. 2004a) on board the *Spitzer* Space Telescope. IRAC has four wavelength bands centered at 3.6, 4.5, 5.8, and 8.0  $\mu\text{m}$ , each of which has a field of view of  $\sim 5'.2 \times 5'.2$ . The pixel size in all the four bands is  $\sim 1''.22$ . The Corrected Basic Calibrated Data (CBCD) images were downloaded from the *Spitzer* Space Telescope Archive using the Leopard package. The IRAC observations of the region were taken on 2006 November 25 (Program ID 30734, AOR key 18902784: Massive Star Clusters, PI: Donald Figer). Mosaics were built at the native instrument resolution of  $1''.22$  per pixel with the standard BCDs using the MOPEX (Mosaicker and Point Source Extractor) software program provided by *Spitzer* Science Center.

We performed aperture photometry on the IRAC images using the DAOPHOT package of IRAF, with a source detection at the  $5\sigma$  level above the average local background. Due to the crowded nature of the field, an aperture radius of 2 pixels and a sky annulus extending from 2 to 6 pixels was used. We adopted the zero-point magnitudes for the standard aperture radius (10 pixels) and background annulus of (10-20 pixels) of 19.67, 18.92, 16.86, and 17.39 mag in the 3.6, 4.5, 5.8, and 8.0  $\mu\text{m}$  bands, respectively, and the appropriate aperture corrections were made using the values described in the IRAC Data Handbook<sup>5</sup>. To estimate the contamination due to non YSO candidates, we analyzed a control field (Program ID 30734, AOR key 18902784: Galactic structure, PI: Steven Majewski) located approximately 1.1 degrees away from the target field with no obvious signs of star formation, using the same procedure as described above. For both the fields the sources which have photometric uncertainties less than 0.2 mag are considered as good detections. This should be considered as conservative lower limit as the calibration uncertainty associated with the IRAC bands is 2-3% and in addition, there are 1-2% uncertainty in the aperture corrections.

## 3. RESULTS

### 3.1. Morphology of Sh2-294

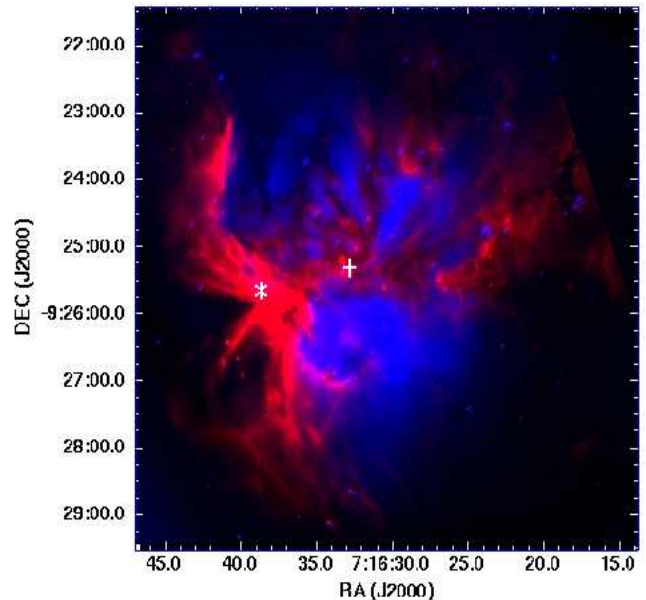


FIG. 1.— *Spitzer*-IRAC 8  $\mu\text{m}$  image (red) superimposed on H $\alpha$  line image (blue) of Sh2-294 region (for colour plot see online electronic version). The image has a field of view  $\sim 8' \times 8'$ . The plus and asterisk symbols show the positions of the exciting source of Sh2-294 and of the massive B1.5 source at its border, respectively.

Figure 1 shows a colour composite image of H $\alpha$  emission (taken from Paper-I) superimposed with the IRAC 8  $\mu\text{m}$  emission. The plus symbol in the image marks the position of the exciting source of Sh2-294. The position of the massive B1.5 source associated with “region A” is marked with an asterisk symbol (see §1). The 8  $\mu\text{m}$  IRAC band contains emission bands at 7.7 and 8.6  $\mu\text{m}$  commonly attributed to PAH molecules. PAHs are believed to be destroyed in the ionized gas, but thought to be excited in the PDR at the interface of H II region and molecular cloud by the absorption of far-UV photons leaking from the H II region. Therefore, PAHs are good tracers of the hot PDR that surrounds the H II region.

Figure 1 also reveals the distribution of 8  $\mu\text{m}$  emission in a filamentary fashion with its long axis aligned in east-west direction that bisects the H II region and the ionized gas appears to be streaming away orthogonal to the long axis. In both sides of the filament axis, the ionized gas shows decrease in intensity possibly due to the density gradient in the original medium. The ionized gas is bounded more in the eastern direction as compared to in western direction, however, the overall morphology of the nebula looks bipolar in nature. The bipolar morphology have been noticed in NIR to MIR bands in few H II regions and/or bubbles (see e.g., Churchwell et al. 2006; Saito et al. 2009). Now long wavelength observation ( $> 100 \mu\text{m}$ ) with *Herschel* has added new insight to this morphology. For example, the recent finding by Deharveng et al. (2012) with *Herschel* observations, the H II region “Sh2-201”, illustrates a clear bipolar morphological nature, with two bipolar lobes perpendicular to a dense neutral filament extending east-west. The two lobes seem to be bounded by cold neutral material of low column density ( $\leq 10^{21} \text{ cm}^{-2}$ ), whereas the column density is high ( $> 10^{22} \text{ cm}^{-2}$ ) on each side at the waist of the Sh2-201 along the parental filament (Deharveng et al. 2012). Bipolar H II regions are believed to be formed in

<sup>5</sup> <http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac>

TABLE 1

PHOTOMETRIC DATA AT IRAC BANDS. A SAMPLE OF THE TABLE IS GIVEN HERE. THE COMPLETE TABLE IS AVAILABLE IN ELECTRONIC FORM.

RA (deg) J2000	DEC (deg) J2000	[3.6] mag	[4.5] mag	[5.8] mag	[8.0] mag
109.124010	-9.495950	11.942 $\pm$ 0.009	11.927 $\pm$ 0.012	11.942 $\pm$ 0.023	11.949 $\pm$ 0.076
109.167320	-9.489430	11.075 $\pm$ 0.006	11.054 $\pm$ 0.009	11.135 $\pm$ 0.015	11.060 $\pm$ 0.045
109.142310	-9.485300	9.981 $\pm$ 0.004	10.008 $\pm$ 0.005	9.995 $\pm$ 0.009	9.875 $\pm$ 0.040

a filamentary cloud. Due to the absence of sensitive long wavelength observations, it is hard to imagine the shape and structure of the original cloud, on a large scale in which Sh2-294 has formed. However, we shall discuss the importance H II region evolution in a filamentary cloud as well as in a hierarchical clumpy cloud on the perspective of future star formation processes in Section 5.1.

### 3.2. Identification of Young Stellar Objects

The circumstellar dust emission from the disk and infalling envelope of YSOs gradually disappears with time. The sequence of evolutionary phases of a YSO: embedded in a circumstellar envelope and an accretion disk (Class I), a classical T Tauri star surrounded by an optically thick disk (Class II), and a weak-line T Tauri star with an optically thin disk (Class III), are generally classified with slopes of SEDs between 2 to 20  $\mu\text{m}$  (Lada & Wilking 1984; Lada 1987). The IRAC [3.6]-[4.5]/[5.8]-[8.0] and [3.6]-[4.5]/[4.5]-[5.8] colour-colour (CC) diagrams are also used as tools to identify different classes of sources (cf. Allen et al. 2004; Hartmann et al. 2005) and follow a similar classification. Restricting our analysis to the sources having photometric error less than 0.2 mag, we detected 102 sources in 3.6, 4.5 and 5.8  $\mu\text{m}$  bands and 31 sources in all the IRAC bands in a common area of  $\sim 6'.8 \times 6'.8$ . These catalogues are made after removing three sources that appear to be extended and/or multiple sources in the high resolution H<sub>2</sub> (2.12  $\mu\text{m}$ ) and 3.6  $\mu\text{m}$  IRAC images. The final catalogue of the identified YSOs in the present analysis is given in Table 1. A sample of the Table 1 is given here, whereas the complete table is available in electronic form as part of the online material. The H<sub>2</sub> mosaic image was constructed using the observations made with ISAAC camera of VLT. The data were retrieved from the ESO archive<sup>6</sup>. Further details about the observations are described in Yun et al. (2008).

The IRAC [3.6]-[4.5]/[5.8]-[8.0] CC diagram is shown in the left panel of Figure 2. Following the classification scheme by Allen et al. (2004) and Hartmann et al. (2005), the regions in the CC diagram occupied by Class II, Class I/II and Class 0/I objects are indicated. The sources with the colour of stellar photosphere are centered around (0, 0); they include foreground, MS as well as Class III objects. The objects with  $0.0 \leq [3.6] - [4.5] \leq 0.8$  and  $0.4 \leq [5.8] - [8.0] \leq 1.1$  are classified as Class II objects. The boundary for Class II sources is marked with a box and are represented by squares. The dotted lines with  $[3.6] - [4.5] \geq 0.7$  and  $[5.8] - [8.0] \geq 0.7$  discriminate Class 0/I (triangles) sources from Class II sources (Hartmann et al. 2005). The zone with  $[5.8] - [8.0] \geq 1.1$  and  $[3.6] - [4.5]$  between 0.0 and 0.7 can be occupied by Class 0/I/II sources. Since Class 0 sources are generally not visible at wavelengths shorter than 10  $\mu\text{m}$ , thus

these objects are likely to be Class I/II sources and are shown with hexagon symbols. On the basis of the above criteria, the [3.6]-[4.5]/[5.8]-[8.0] CC diagram yields 20 YSOs. The search of YSOs on the basis of IRAC [3.6]-[4.5]/[5.8]-[8.0] CC diagram might have been affected by the lower sensitivity of the IRAC 8.0  $\mu\text{m}$  band to detect faint sources and also by the bright background PAH emission. Therefore, in order to detect additional YSOs, we use IRAC [3.6]-[4.5]/[4.5]-[5.8] CC diagram shown in the right panel of Figure 2. Hartmann et al. (2005) show that the division between Class II and Class III T Tauri stars occurs at [3.6]-[4.5] and [4.5]-[5.8]  $\sim 0.2$  with Class III stars are generally situated at  $[3.6] - [4.5] < 0.2$  and  $[4.5] - [5.8] < 0.2$ , whereas most of the Class I/0 protostars are located at  $[3.6] - [4.5] \geq 0.7$  and  $[4.5] - [5.8] \geq 0.7$ . The region with  $[4.5] - [5.8] \geq 0.7$  and  $[3.6] - [4.5]$  between 0.2 to 0.7 is less defined and the overlap between Class I and Class II sources can be seen in well studied star-forming-regions (e.g., Muench et al. 2007; Koenig et al. 2008). On the basis of the above studies, we classify the sources that fall within or to the close vicinity of the boundaries marked in [3.6]-[4.5]/[4.5]-[5.8] CC diagram. They are marked as Class II (squares), Class I (triangles) and Class I/II (hexagon) in Figure 2. It is to be noted that all the sources that show the characteristic of YSOs in IRAC [3.6]-[4.5]/[5.8]-[8.0] CC diagram are also identified as YSOs in [3.6]-[4.5]/[4.5]-[5.8] CC diagram. However, it is possible that some of the sources identified as Class II may be reddened field stars/Class III sources.

The sample of YSOs identified on the basis of MIR-CC diagram may be contaminated by background dusty active galactic nuclei (AGN) and asymptotic giant branch (AGB) stars as they have colours similar to that of YSOs. In nearby SFRs, Fazio et al. (2004b) found that 50% of the sources with  $[3.6] \text{ mag} > 14.5$  are extragalactic in nature. In our sample, we have only 3 common sources in the first three bands of IRAC, that have  $[3.6] \text{ mag} > 14.5$ . We visually inspected these sources in VLT H<sub>2</sub> and *Spitzer* 3.6  $\mu\text{m}$  images, and in both the images they appear as a point-like stellar object. We used a statistical approach to estimate the contamination in the sample of the identified YSOs by comparing the MIR-CC diagram of a control field (not shown) located at  $\alpha_{2000} = 07^h 14^m 49^s$ ,  $\delta_{2000} = -10^\circ 27' 39''$  having an almost equal area to that of the Sh2-294 H II region. Using the same diagnostic approach as described above, we find only 3 objects lying in the Class II and Class I zone of the MIR CC plot. This comparison suggests that the expected number contamination to the YSO population of Sh2-294 region is likely to be less than 10%. Figure 3 shows  $J - H/H - K$  CC diagram for the identified YSOs. The NIR counterparts were identified using a matching radius of  $1''.22$ . In Figure 3, the IRAC classified Class II, Class I/II and Class I YSOs are labeled with the numbers 1-25, T1-T5 and C1-C3, respectively. Majority of

<sup>6</sup> <http://archive.eso.org/eso/eso-archive-main.html>

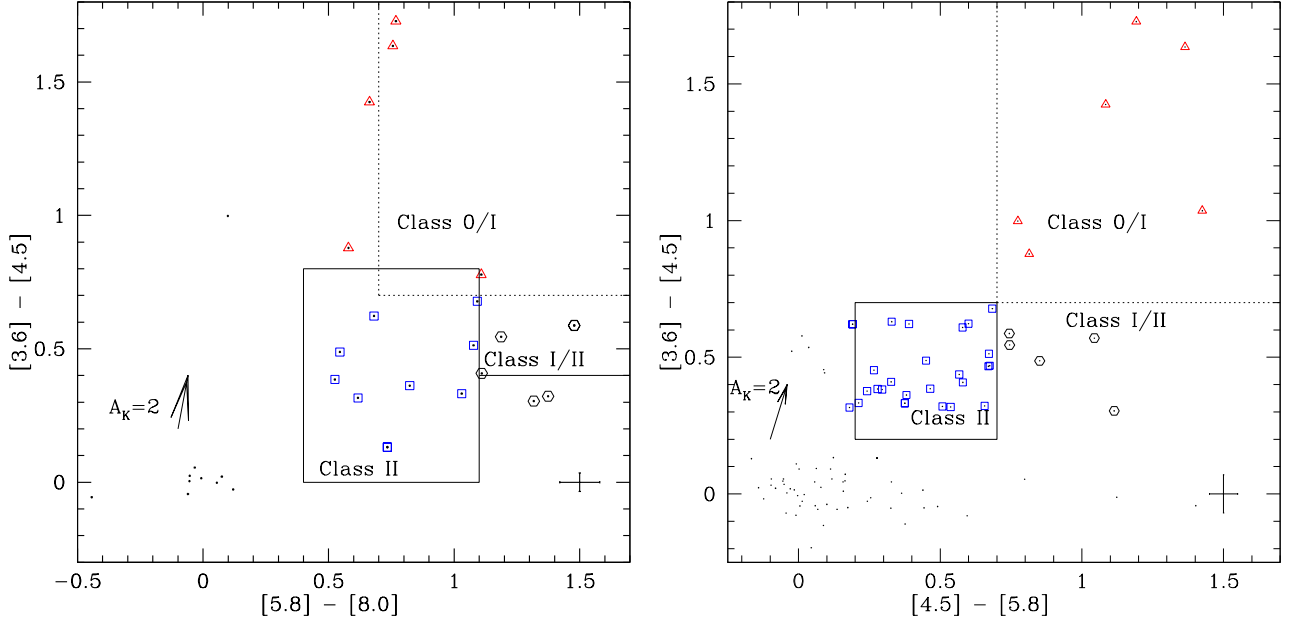


FIG. 2.— Left: IRAC  $[3.6]-[4.5]/[5.8]-[8.0]$  CC diagram with boxes representing the boundaries of different class of sources. Right: IRAC  $[4.5]-[5.8]/[3.6]-[4.5]$  CC diagram with boxes representing the boundaries of different class of sources (see text for details). A reddening vector of  $A_K = 2$  mag, using extinction law of Flaherty et al. (2007) and mean error bars of the colours are shown in both the IRAC CC diagrams.

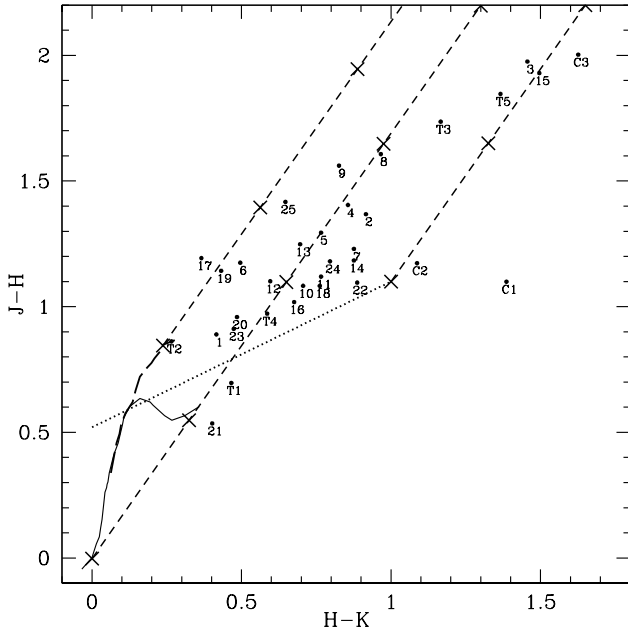


FIG. 3.— NIR CC diagram for all the YSOs that have  $JHK$  counterparts. The thin solid line and thick dashed curves represent the unreddened MS and giant branches (Bessell & Brett 1988), respectively. The dotted line indicates the locus of intrinsic CTTSs (Meyer et al. 1997). The curves and the colours are converted to the California Institute of Technology (CIT) system. The parallel dashed lines are the reddening vectors drawn from the tip of the giant branch (“upper reddening line”), from the base of the MS branch (“middle reddening line”) and from the base of the tip of the intrinsic CTTS line (“lower reddening line”), with crosses at every 5 mag of visual extinction. The numbers 1-25, represent IRAC Class II sources, whereas T1-T5 and C1-C3 denote to the Class I/II and Class I sources, respectively. The magnitudes for C1 and C2 in  $J$  and  $H$  bands are the upper limit, therefore their locations in the CC diagram are not the real.

the identified YSOs (barring T1 and 21) lie above the locus of the Classical T Tauri stars (CTTS) locus given by Meyer et al. (1997), indicating that these could be the probable CTTSs. A comparison of the positions of these YSOs in the NIR CC diagram (cf. Figure 3), with the CC diagram of the control field (see Figure 9(b) of Samal et al. 2007), again suggests that most of the sources identified using IRAC CC diagrams are most likely YSO candidates. However, the positions of sources 17, 19, 21 and T2 in the NIR CC diagram is not compatible with Class II sources. The sources 17, 19 and T1 fall in the close vicinity of the leftmost reddening vector that starts from the tip of unreddened giant locus, whereas the position of the source 21 falls far below the T-Tauri locus. The positions of these sources in the NIR CC diagram also mimic with the positions of the field star distribution of the control field. Moreover, the spatial positions of three sources (17, 19 & 21) show that they are away from the cluster center (see §3.4).

From IRAC photometry, we find a total of 36 likely YSO candidates, indicating that star formation is still active in the region. It is not possible to distinguish Class III YSOs from the MS and/or field stars with the existing photometric data alone. Spectroscopic data and/or X-ray observations are needed to confirm the YSO nature of the Class III sources. The X-ray emission in case of Class III stars is elevated by a factor of  $10^{3-4}$  compared to the MS stars (Walter & Barry 1991). In the present analysis, we restrict ourselves with these more reliable sample of Class I and Class II YSOs. In the following sections, we have used the spatial distribution of the identified YSOs and their characteristics to study the star formation scenario in Sh2-294 H II complex.

### 3.3. $H_2$ structures

The morphology of Sh2-294 region (see Figure 1) suggests that as the ionized gas streams away from the cen-

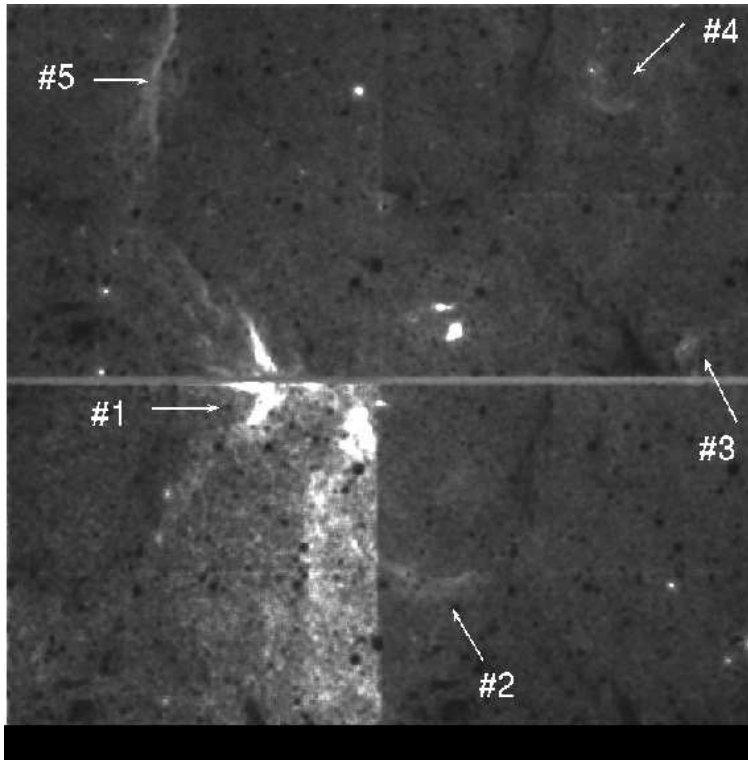


FIG. 4.— Median smoothed with the stars subtracted  $H_2$  image at  $2.12 \mu m$ . The positions of the enhanced emissions are marked as numbers. The point-like sources seen in the above smoothed image are the product of the residuals that left in case of bright saturated stars. The image is centered on  $\alpha_{2000} = 17^h 16^m 32^s$ ,  $\delta_{2000} = -09^\circ 25' 32''$  and has a field of view  $\sim 5'.2 \times 5'.2$ . North is up and east is to the left.

ter, it possibly encounters an inhomogeneous medium, illustrating patchy, clumpy and knotty structures, which can be seen at *Spitzer*  $8 \mu m$  emission. In order to correlate the structures seen in  $8 \mu m$ , the positions of the detected YSOs and the  $H_2$  emissions, we used the deep image at  $2.12 \mu m$ , 1-0 S(1) line of  $H_2$ , obtained with the VLT. The present  $H_2$  image is considerably more sensitive and has higher angular resolution than that presented in Paper-I. Figure 4 displays the  $H_2$  image at  $2.12 \mu m$ , which reveals strong emission along the eastern border of the H II region, as well as notable features at various locations of the nebula, which are numbered as #1 to #5. The diffuse  $H_2$  emission can be excited by Lyman and Werner UV photons (e.g., Chrysostomou et al. 1992) from the massive stars and thus can trace PDR or can be due to collisional excitation in the presence of shocks arising from outflows from nearby YSOs. For dense gas ( $n_H \sim 10^5 \text{ cm}^{-3}$ ),  $H_2$  emission alone cannot be used to identify PDR as UV excitation levels can be collisionally redistributed (see Allen et al. 1999), hence another PDR tracer like PAH emission is necessary to trace PDR around a nebula (Giard et al. 1994). Though, the spectroscopic observations of  $H_2$  lines and their ratios would rather provide the exact nature of the excitation (see Luhman et al. 1998), however, close resemblance of diffuse  $H_2$  emission with the  $8 \mu m$  emission (see Figure 1), suggests the  $H_2$  emissions at the periphery of Sh2-294 are more likely caused by UV fluorescence. The identified  $H_2$  structures are of particular interest as they show rim or arc-like morphology, with either the rim faces towards the ionizing source at the center or the curvature of arc (e.g., #2) appears to be created by the UV photons of ionizing star. The morphology suggests that the weak

$H_2$  and PAH emissions associated with the Sh2-294 region possibly correspond to UV excited positions of the dense condensations or fragments of the original molecular cloud in which Sh2-294 was born. However, high resolution and high sensitive molecular line observations are needed to reveal the truth. Here, we presume that these dusty structures are associated with the Sh2-294 SFR because the rims/carved arcs are facing towards the ionizing star and exhibit externally heated structures, as expected in case of motionless cloud exposed to strong UV radiation from nearby massive star(s).

### 3.4. Spatial distribution of YSOs

We identified 36 YSOs (6 Class I, 25 Class II, and 5 Class InII) using IRAC CC diagrams; the spatial distribution of these YSOs on  $5.8 \mu m$  image is shown in Figure 5. The YSOs are labeled in the same manner as in Figure 3. Figure 5 indicates that the YSO candidates are preferentially located in/around regions with diffuse  $5.8 \mu m$  emission. It is found that all the Class I sources are located at the outer regions, whereas majority of the Class II sources are found to be concentrated around the proximity of the ionizing source. If Class I sources are really the precursors to Class II sources, as expected from their less evolved circumstellar environments, they should have younger ages. Hence, the distribution of Class I sources indicates that the star formation seems to be continued near the outer parts of the H II region. The YSOs C1, C2, C3, C4, C6, 1 and 25 are of particular interest because of their association with the  $H_2$  structures (as marked in Figure 5) and PAH emissions.

The IRAC sensitivity and bright diffuse PAH emissions at  $5.8$  and  $8.0 \mu m$  band could be one of the issues



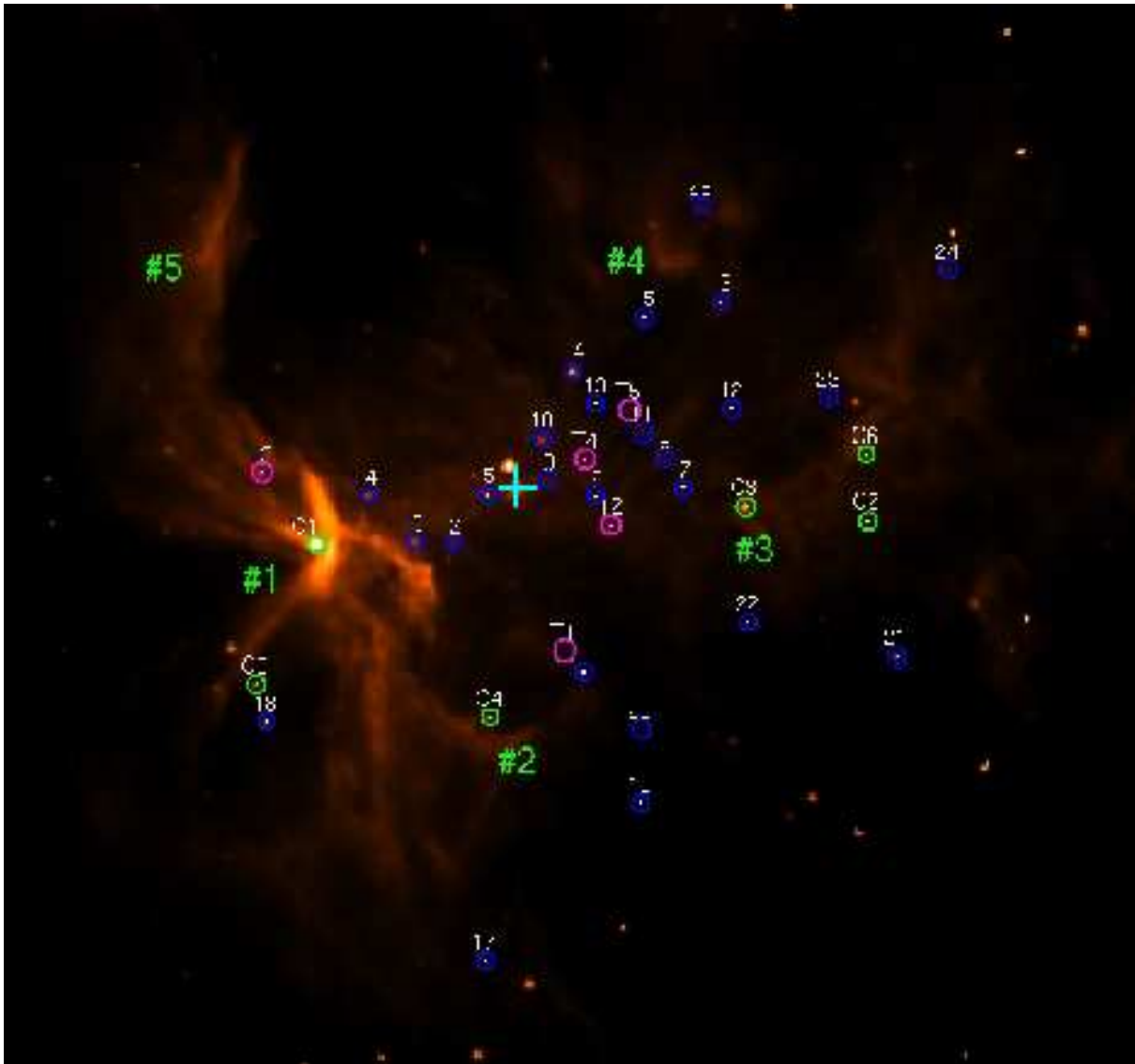


FIG. 5.— Spatial distributions of Class II (blue circles), Class I (green circles) and Class I/II (magenta circles) overlaid on the  $5.8 \mu\text{m}$  image (for colour plot see online electronic version). The image has a field of view  $\sim 7'.2 \times 7'.2$  and is centered on  $\alpha_{2000} = 17^h 16^m 32^s$ ,  $\delta_{2000} = -09^\circ 25' 32''$ . The YSOs are labeled in the same manner as in Figure 3. The plus symbol shows the position of the ionizing source. The enhanced  $\text{H}_2$  structures are leveled as in Figure 4. North is up and east is to the left.

for the detection of lower number of YSOs. We carried out the quantitative evaluation of the completeness of the photometric data with respect to the brightness and the position by adding artificial stars to both  $5.8$  and  $8.0 \mu\text{m}$  images. The ratio of the number of stars recovered to those added in each magnitude interval gives the completeness factor as a function of magnitude. We found that the completeness in the central region is  $\sim 80\%$  to the level of  $\sim 14.0$  mag and  $\sim 12.0$  mag at  $5.8 \mu\text{m}$  and  $8.0 \mu\text{m}$ , respectively. However, in the regions of diffuse emissions (e.g., #1), the completeness decreases to  $50\%$  at magnitudes  $\sim 14.0$  and  $\sim 12.0$  at  $5.8 \mu\text{m}$  and  $8.0 \mu\text{m}$ , respectively. Only one Class I YSO has been identified in the region #1 on the basis of IRAC data. The lower detection of YSOs could be the result of decrease in sensitivity due to the bright PAHs as obvious from the completeness analysis.

### 3.5. Physical properties of YSOs

To get deep insight into the nature of the YSOs identified in the present work, we constructed SEDs using the models and fitting tools of Robitaille et al. (2006, 2007). The models are computed using a Monte-Carlo based radiation transfer code (Whitney et al. 2003a,b), which uses several combinations of central star, accreting disk, in-falling envelope and bipolar cavity for a reasonably large parameter space. Interpreting SEDs using the radiative transfer code is subject to degeneracies and spatially resolved multiwavelength observations can break the degeneracy. To constrain the parameters of stellar photosphere and circumstellar environment, we fit the SEDs to only those sources for which we have a minimum of 6 data points in the wavelength range from  $0.55$  to  $8 \mu\text{m}$ . We search the counterparts of the identified YSOs in the optical-NIR bands by Yun et al. 2008 and in Two Micron All Sky Survey (2MASS) point source catalogue (Curti et al. 2003), using a matching radius of  $1''.22$ . This yields 33 sources detected in 6 bands or

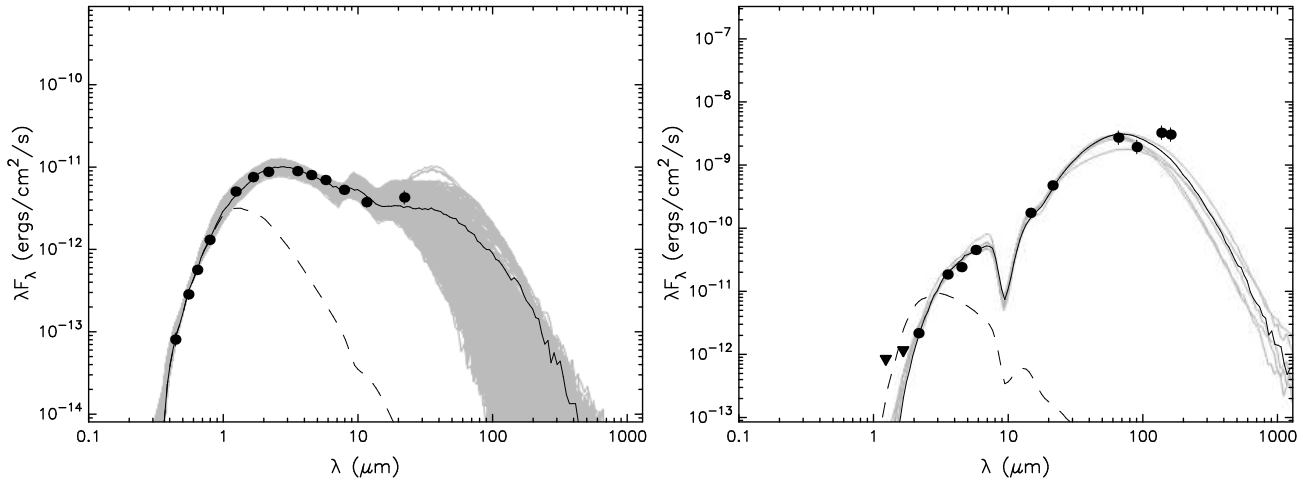


FIG. 6.— The SEDs for a Class II (Left) and Class I (Right) source. (Left): The SEDs for the source 14. The black line shows the best fit, and the grey lines show subsequent good fits with  $\chi^2 - \chi^2_{\min} \leq 2N_{\text{data}}$ . The dashed line shows the stellar photosphere corresponding to the central source of the best fitting model. The filled circles denote the input flux values. (Right): The SED for the source C1. The lines are of same meaning as in Left figure. The filled circles denote the input flux values. The triangles are upper limits for the flux values at  $J$  and  $H$  bands, taken from 2MASS. The flux values at 14.65 and 21.30  $\mu\text{m}$  are from *MSX* point source catalog (Egan et al. 2003) for the source G224.1880+01.2407 and the fluxes at 65, 90, 140 and 160  $\mu\text{m}$  are from AKARI Far-Infrared Surveyor catalog (Yamamura et al. 2009) for the source 0716378-092559.

more ranging from optical (*VRI*) to IRAC (3.6, 4.5, 5.8, 8.0  $\mu\text{m}$ ) bands, which include 21 sources having optical counterparts. Out of 33 sources which have minimum 6 data points, 25 of them have fluxes at four wavebands of Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) survey. The WISE bands have central wavelengths at 3.4, 4.6, 12, and 22  $\mu\text{m}$ , with spatial resolutions of 6''.1, 6''.2, 6''.5, and 12''.0, respectively. As stated in Robitaille (2008), the SED fitting tool deals with a single source and input fluxes from multiple sources in a beam can result in incorrect stellar age and mass. Similarly, any erroneous fluxes can seriously affect the chances of obtaining sensible SED, thus sensible physical parameters. As there is strong clustering of point sources seen in IRAC 4.5  $\mu\text{m}$  image (not shown), along with bright nebulosities found in WISE 12  $\mu\text{m}$  and 22  $\mu\text{m}$  image, we therefore limited the use of WISE fluxes by preferring IRAC 3.6  $\mu\text{m}$  and 4.5  $\mu\text{m}$  fluxes over WISE 3.4  $\mu\text{m}$  and 4.6  $\mu\text{m}$ , due to superior spatial resolution of IRAC bands. Similarly, we use only those fluxes at 12  $\mu\text{m}$  and 22  $\mu\text{m}$  as inputs which have good-quality flags. We also set an upper limit at 22  $\mu\text{m}$  for those sources for which we do not have detection, by assigning the minimum 22  $\mu\text{m}$  flux that found in our sample of YSO. The SED fitting tool fits each of the models to the data, allowing the distance and external foreground extinction as free parameters. Since we do not have spectral type information for our identified YSOs, in order to derive their approximate extinction values, we traced back these sources along the reddening vector to the intrinsic late MS locus or its extension in the NIR CC diagram (e.g., Tej et al. 2006). Considering the uncertainties that might have gone into the estimates, we used the estimated value  $A_V \pm 2.5$  mag, as an input parameter for these sources. For Class I sources, for which we do not have NIR data, we allow  $A_V$  up to 30 mag. We further set 10% to 30% error in the flux estimates due to possible uncertainties in the calibration and intrinsic object variability. Figure 6 shows an example of SEDs of the resulting models for the Class II and Class I sources. We obtained physical parameters for all

the sources adopting the approach similar to Robitaille et al. (2007) by considering those models that satisfy  $\chi^2 - \chi^2_{\min} \leq 2N_{\text{data}}$ , where  $\chi^2_{\min}$  is the goodness-of-fit parameter for the best-fit model and  $N_{\text{data}}$  is the number of input observational data points. The parameters are obtained from the weighted mean and standard deviation of these models, weighted by  $e^{(-\chi^2/2)}$  of each model and are tabulated in Table 2. These parameters are obtained from set of models that represent the overall distribution, therefore more likely suppress any extreme values which may arise due to few badly fitted models. However, due to limited observational data points, some of the parameters from the model fits can be narrowly constrained over others depending upon the available fluxes. Since we are mainly interested in stellar parameters due to availability of shorter wavelength fluxes, we therefore only quote few parameters from the 14 parameter space SED models. Table 2 lists the star mass ( $M_*$ ), temperature ( $T_*$ ), stellar age ( $t_*$ ), mass of the disk ( $M_{\text{disk}}$ ), disk accretion rate ( $\dot{M}_{\text{disk}}$ ), foreground visual absorption ( $A_V$ ) and the  $\chi^2_{\min}$  of the best fit. Table 2 reveals that the ages of the majority of Class II YSO (excluding 17) candidates vary between 1.5 to  $7 \times 10^6$  yr with a median age of  $4.5 \pm 1.9 \times 10^6$  yr, whereas the visual extinction varies from 3.2 to 13.5 mag, indicating presence of non-uniform extinction within the region. Out of 25 Class II sources, 18 sources have fluxes at optical wavelengths, thus their age estimations expected to be better constrained, which is  $5.1 \pm 1.4 \times 10^6$  yr (median age). From Table 2, it appears that the YSOs identified in the present work are detected nearly down to  $\sim 1.8 M_\odot$  and probably a large number of low mass YSOs are embedded in the cloud. We note that the stellar ages given in Table 2 are only approximate. Spectroscopic observations of the YSOs would be more accurate in the determination of their stellar age. In Robitaille et al. (2007) models, the stellar masses and ages are sampled using the isochrones and evolutionary tracks (Bernasconi & Maeder 1996; Siess et al. 2000) from the stellar luminosity and temperature, de-

TABLE 2  
INFERRED PHYSICAL PARAMETERS FROM SED FITS TO YSOs

ID	RA (deg) (J2000)	DEC (deg) (J2000)	$M_*$ ( $M_\odot$ )	$T_*$ ( $10^3$ K)	$t_*$ ( $10^6$ yr)	$M_{\text{disk}}$ ( $M_\odot$ )	$\dot{M}_{\text{disk}}$ ( $10^{-8} M_\odot/\text{yr}$ )	$A_V$ mag	$\chi^2$
1	109.130424	-9.443050	$1.99 \pm 0.36$	$5.83 \pm 1.23$	$4.85 \pm 2.64$	$0.009 \pm 0.012$	$3.97 \pm 3.66$	$3.82 \pm 0.59$	2.82
2	109.145180	-9.428912	$2.19 \pm 0.37$	$8.68 \pm 1.64$	$6.99 \pm 2.42$	$0.006 \pm 0.013$	$3.44 \pm 3.42$	$8.13 \pm 0.53$	0.89
3	109.149498	-9.428577	$3.00 \pm 0.47$	$11.03 \pm 1.80$	$5.10 \pm 2.41$	$0.003 \pm 0.009$	$1.12 \pm 1.61$	$13.59 \pm 1.15$	8.05
4	109.154785	-9.423507	$2.53 \pm 0.53$	$8.01 \pm 2.13$	$4.45 \pm 1.33$	$0.004 \pm 0.007$	$4.47 \pm 4.54$	$8.72 \pm 0.50$	0.98
5	109.141357	-9.423445	$2.87 \pm 0.65$	$9.75 \pm 3.12$	$4.99 \pm 2.43$	$0.005 \pm 0.016$	$2.30 \pm 2.77$	$7.61 \pm 0.73$	1.05
6	109.128922	-9.423709	$2.24 \pm 0.35$	$9.01 \pm 1.57$	$7.66 \pm 1.62$	$0.001 \pm 0.003$	$0.84 \pm 0.86$	$7.35 \pm 0.67$	4.07
7	109.118996	-9.422717	$2.25 \pm 0.34$	$9.14 \pm 1.52$	$7.55 \pm 1.34$	$0.001 \pm 0.004$	$0.75 \pm 0.81$	$7.56 \pm 0.52$	20.35
8	109.134392	-9.421776	$2.44 \pm 0.55$	$7.65 \pm 2.72$	$4.47 \pm 2.79$	$0.007 \pm 0.016$	$3.36 \pm 4.55$	$10.90 \pm 0.90$	2.28
9	109.121185	-9.419425	$3.50 \pm 0.83$	$7.49 \pm 4.17$	$1.56 \pm 0.98$	$0.011 \pm 0.018$	$10.83 \pm 10.68$	$10.03 \pm 1.50$	4.85
10	109.135048	-9.417233	$4.85 \pm 0.31$	$16.10 \pm 1.03$	$4.93 \pm 0.98$	$0.000 \pm 0.001$	$0.04 \pm 0.04$	$6.64 \pm 0.30$	7.30
11	109.123581	-9.416539	$2.31 \pm 0.48$	$5.69 \pm 1.03$	$3.23 \pm 2.24$	$0.010 \pm 0.019$	$2.80 \pm 2.65$	$6.38 \pm 0.59$	1.45
12	109.113495	-9.413931	$1.98 \pm 0.33$	$5.15 \pm 0.84$	$3.17 \pm 2.30$	$0.006 \pm 0.015$	$1.35 \pm 4.10$	$5.45 \pm 0.45$	1.92
13	109.128975	-9.413376	$2.28 \pm 0.27$	$9.48 \pm 1.19$	$8.09 \pm 1.15$	$0.002 \pm 0.005$	$0.16 \pm 0.16$	$7.63 \pm 0.46$	8.45
14	109.131577	-9.409706	$3.09 \pm 0.33$	$11.14 \pm 1.26$	$3.71 \pm 1.64$	$0.013 \pm 0.019$	$1.43 \pm 1.42$	$6.33 \pm 0.16$	4.45
15	109.123474	-9.403764	$4.64 \pm 1.01$	$4.65 \pm 0.27$	$0.17 \pm 0.13$	$0.007 \pm 0.017$	$3.88 \pm 3.88$	$13.49 \pm 0.39$	17.58
16	109.114693	-9.401979	$3.16 \pm 0.63$	$11.39 \pm 2.68$	$5.24 \pm 1.99$	$0.002 \pm 0.010$	$2.85 \pm 3.59$	$4.85 \pm 0.58$	2.38
17	109.141520	-9.475020	$0.60 \pm 0.79$	$3.46 \pm 0.59$	$0.10 \pm 0.13$	$0.007 \pm 0.008$	$28.69 \pm 28.04$	$5.40 \pm 0.27$	8.85
18	109.166450	-9.448670	$1.89 \pm 0.53$	$6.59 \pm 2.74$	$3.32 \pm 3.21$	$0.036 \pm 0.028$	$52.65 \pm 39.97$	$4.95 \pm 0.96$	4.35
19	109.123810	-9.457560	$2.57 \pm 0.74$	$8.61 \pm 3.76$	$4.66 \pm 1.20$	$0.000 \pm 0.000$	$0.06 \pm 0.05$	$6.22 \pm 1.13$	1.95
20	109.123770	-9.449440	$1.88 \pm 0.46$	$5.20 \pm 0.40$	$4.82 \pm 2.52$	$0.007 \pm 0.011$	$1.15 \pm 1.05$	$4.34 \pm 0.32$	3.15
21	109.094720	-9.441330	$4.79 \pm 0.10$	$16.04 \pm 0.21$	$4.07 \pm 0.28$	$0.000 \pm 0.000$	$0.00 \pm 0.00$	$3.10 \pm 0.34$	11.15
22	109.111640	-9.437610	$3.57 \pm 0.38$	$12.30 \pm 3.08$	$5.73 \pm 2.30$	$0.000 \pm 0.002$	$0.07 \pm 0.07$	$6.75 \pm 1.31$	25.51
23	109.102440	-9.412630	$3.60 \pm 0.30$	$12.38 \pm 3.06$	$5.91 \pm 2.26$	$0.000 \pm 0.000$	$0.03 \pm 0.03$	$6.76 \pm 1.32$	6.45
24	109.088880	-9.398560	$1.22 \pm 0.54$	$4.18 \pm 0.58$	$0.07 \pm 0.28$	$0.038 \pm 0.034$	$37.83 \pm 37.80$	$6.20 \pm 0.76$	10.51
25	109.116930	-9.391600	$3.62 \pm 0.29$	$12.97 \pm 1.09$	$4.29 \pm 1.94$	$0.000 \pm 0.000$	$0.00 \pm 0.00$	$5.81 \pm 0.84$	8.67
T1	109.132507	-9.440776	$2.27 \pm 1.22$	$4.97 \pm 0.59$	$3.10 \pm 2.38$	$0.014 \pm 0.015$	$7.91 \pm 7.90$	$5.33 \pm 0.62$	13.29
T2	109.127251	-9.426885	$2.32 \pm 0.58$	$6.90 \pm 1.91$	$4.37 \pm 2.55$	$0.011 \pm 0.017$	$34.07 \pm 33.95$	$3.34 \pm 0.71$	2.63
T3	109.166985	-9.420988	$5.87 \pm 0.96$	$5.10 \pm 0.65$	$0.16 \pm 0.12$	$0.052 \pm 0.086$	$149.58 \pm 149.45$	$11.40 \pm 1.01$	6.23
T4	109.130173	-9.419502	$1.82 \pm 0.90$	$5.39 \pm 2.27$	$0.80 \pm 1.26$	$0.026 \pm 0.028$	$73.84 \pm 73.34$	$10.08 \pm 0.83$	8.87
T5	109.125168	-9.414126	$0.76 \pm 0.42$	$4.00 \pm 0.43$	$0.29 \pm 1.09$	$0.004 \pm 0.009$	$4.28 \pm 4.27$	$3.54 \pm 0.35$	7.74
C1	109.162000	-9.428901	$8.78 \pm 1.67$	$6.12 \pm 1.61$	$0.04 \pm 0.04$	$0.199 \pm 0.274$	$390.00 \pm 383.00$	$23.70 \pm 6.69$	35.89
C2	109.098038	-9.426320	$2.81 \pm 0.78$	$4.51 \pm 0.19$	$0.17 \pm 0.09$	$0.008 \pm 0.018$	$6.94 \pm 6.94$	$6.16 \pm 1.35$	10.15
C3	109.111923	-9.424769	$2.66 \pm 1.93$	$5.82 \pm 4.75$	$0.37 \pm 1.03$	$0.034 \pm 0.048$	$112.23 \pm 110.78$	$14.17 \pm 1.21$	18.19

rived from the SED models. Since the age determination for all the YSOs is being done following the same set of evolutionary tracks and the same approach, we therefore use the relative age among the YSOs to constrain the star formation history of the complex. However, we are aware of the fact that age estimation depends upon the choice of isochrones. For example, Hillenbrand et al. (2008) suggested use of different set of isochrones can lead to a systematic uncertainty at a level of 0.75 dex for sub-solar mass stars, though the agreement is better for older PMS solar-mass stars. Out of six Class I sources identified in the present study, only three (C1, C2 & C3) have sufficient data points to fit the models of Robitaille et al. (2007). The models predict that all the three sources are young ( $\leq 0.4 \times 10^5$  yr) and have relatively massive disk in comparison to the Class II sources of the region. The age estimation of the accreting embedded protostars probably more uncertain, therefore, should be considered as quantitative indicator of stellar youth. Though, we do not have sufficient data to address the evolutionary status of other Class I YSOs (C4, C5 & C6), however, the infrared colours of these objects indicate that they must be IR excess stars with circumstellar disk. Here, we assume the age of C4, C5 and C6 must be of the order of few  $\times 10^5$  yr, which is generally attributed to this class of sources (Kenyon & Hartmann 1995). As discussed earlier, most of the Class I sources are distributed away from the central cluster. The Class I sources represent a much younger population than the ionizing source ( $\sim 4$

$\times 10^6$  yr) and the associated Class II sources within the cluster region. It is also apparent from Table 2 that the disk accretion rate of the Class II YSOs, except few outliers, is in the range of  $10^{-7} - 10^{-9} M_\odot \text{ yr}^{-1}$ , which is less than that of Class I/II and Class I YSOs ( $10^{-6} - 10^{-7} M_\odot \text{ yr}^{-1}$ ). It is to be noted that in the absence of far-infrared (FIR) to millimeter data the above values, particularly the disk parameters, should be treated with a caution.

### 3.6. Massive YSO

Samal et al. (2007) on the basis of mid to far-infrared fluxes predicted a presence of a massive ZAMS star in the region #1. In the *Spitzer* image, we identified a luminous source (C1;  $[3.6]=12.1$  mag) located behind the rim like structure seen in  $5.8 \mu\text{m}$  image (see Figure 5). The star is faint in the  $K_s$  band and do not has stellar counterpart in the optical. The SED models of the source based on data from 2MASS (J, H, and  $K_s$ ), *Spitzer* (3.6, 4.5, and  $5.8 \mu\text{m}$ ), MSX survey (14.65 and  $21.30 \mu\text{m}$ ), and AKARI (65, 90, 140 and  $160 \mu\text{m}$ ) are shown in Figure. 6 (right panel). The SED of this YSO candidate is better sampled at longer wavelengths, showing a very steep rise in the  $1.22 \mu\text{m}$  to  $\sim 140 \mu\text{m}$  range, indicating the presence of an envelope thus the object should be a Class I YSO. The parameters from the best fit models suggest that the source has an age of  $\sim 4 \times 10^4$  yr and mass  $\sim 9 M_\odot$  with a total luminosity of  $\sim 1.8 \times 10^3 L_\odot$ . The source is embedded in a cloud having  $A_V \sim 24$  mag and is still accreting with a high envelope accretion rate of



$\sim 9.8 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ . Accreting protostars show signature of outflow in their very young age. Extended  $4.5 \mu\text{m}$  emission often used as a tracer of outflow activity from massive young stellar objects (MYSOs), as the  $4.5 \mu\text{m}$  IRAC band contains both  $\text{H}_2$  ( $v=0-0$ , S(9,10,11)) lines and CO ( $v=1-0$ ) band heads, thus can be excited by shocks such as those expected from protostellar outflows (Cyganowski et al. 2008 and references therein). Outflow sources identified based on their enhanced extended  $4.5 \mu\text{m}$  emission are known as “Extended Green Objects (EGOs)” and are generally identified with color coding using IRAC 3-colour composite images. In search of EGOs, we made a colour-composite (see Figure 7) image using the IRAC first three bands around the MYSO “C1”. The source is embedded in a PDR and PDRs are generally bright in IRAC  $5.8 \mu\text{m}$  and  $8.0 \mu\text{m}$ , thus adds difficulty in search for weak EGOs. In Figure 7, however, we did not find any enhanced emission at  $4.5 \mu\text{m}$ , indicating either the emission is absent or very weak. It has been noticed that the YSOs responsible for outflows appear blue in IRAC  $[3.6]-[4.5]/[4.5]-[5.8]$  CC diagram and are generally located at specific position ( $[3.6]-[4.5] \geq 1.1 \text{ mag}$  and  $[4.5]-[5.8] \leq 0.8 \text{ mag}$ ; Ybarra & Lada 2009 and references therein) in this CC space; thus sometimes used with caution to identify the driving sources. A comparison shows that none of the YSO candidates in our sample are located at the preferred position as mentioned above, in IRAC  $[3.6]-[4.5]/[4.5]-[5.8]$  CC diagram (see Figure 2b), indicating the identified YSOs are probably crossed the outflow stage. A star of  $\sim 9 M_{\odot}$  takes  $\sim 2 \times 10^5 \text{ yr}$  to reach ZAMS (Bernasconi & Maeder 1996) and the evolutionary status (age  $< 10^5 \text{ yr}$ ) of the MYSO based on SED models indicate that the source is still in the PMS phase or about to reach ZAMS. In the PMS phase, the Lyman continuum emission from a massive star is expected to be much lower than its corresponding MS phase. In Paper-I, we found a radio continuum peak in the proximity of structure #1; however, the emission is elongated along the bright arc seen in the  $5.8 \mu\text{m}$  image. The *Spitzer* image reveals that massive source C1 does not exactly coincide with the radio peak, it is rather situated  $\sim 20''$  away in the eastern direction. Though the resolution of the radio continuum image presented in Paper-I, does not allow to conclude about the origin of the radio emission, however, we presume that its elongated structure and its offset from the source C1 possibly represent the ionized gas from the photo-evaporating layer of the externally ionized rim (e.g., Morgan et al. 2004). The high envelope accretion rate indicates that source C1 may become more massive with time and may drive an H II region.

#### 4. DISCUSSION ON STAR FORMATION ACTIVITY

Star formation in a molecular cloud is more active during the first few million year of cloud lifetime. It is believed that majority of the stars in a molecular cloud form in clusters and after few million year star formation, the gas in a molecular cloud dissipates and further star formation no longer takes place (Lada & Lada 2003). It is found that clusters with age greater than  $\sim 5 \times 10^6 \text{ yr}$  are seldom associated with molecular gas (Leisawitz et al 1989), thus it is more likely that after  $\sim 5 \times 10^6 \text{ yr}$  no gas is left over to form new stars. However, these type of molecular cloud complexes can still have star

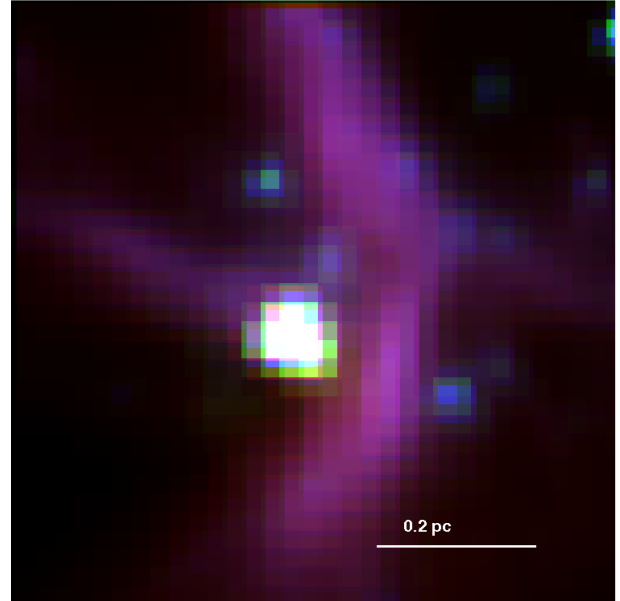


FIG. 7.— The *Spitzer*-IRAC colour-composite image ( $5.8 \mu\text{m}$ , red;  $4.5 \mu\text{m}$ , green; and  $3.6 \mu\text{m}$ , blue) around the massive source C1. North is up and east is to the left.

formation in PDRs at the interface of the H II region and the molecular gas. Many young clusters associated with H II regions show age spread, which is partly due to the cluster evolution and partly due to different epochs of star formation within the region (e.g., Sharma et al. 2007; Pandey et al. 2008; Jose et al. 2008). In Sh2-294 region, with the help of *Spitzer* observations, we detected sources with disk and envelope, evidence of youth of the region. The presence of extremely young Class I sources perhaps represents fresh star formation in the region. The SED models, within the uncertainties, indicate that the age of most of the Class II YSOs are of comparable to ionizing source and these sources are certainly older than Class I YSOs. All the Class I sources are distributed at the outskirts of the Sh2-294 region; most of them are associated with arc-shaped  $\text{H}_2$  structures and PAH features. The distribution of young YSOs at the outskirts of H II regions/bubbles has been noticed in several cases (see e.g., Deharveng et al. 2005; Zavagno et al. 2006; Koeing et al. 2008; Watson et al. 2008; Deharveng et al. 2009; Chauhan et al. 2011), where it is believed that the majority of them are formed as a result of triggered star formation. Although kinematics of the Sh2-294 region is not available, the morphology, the association of Class I YSOs with  $\text{H}_2$  structures and their younger ages with respect to  $4 \times 10^6 \text{ yr}$  massive B0 MS star, give evidence in favor of triggered star formation in the region. On the basis of Hipparcos data, Madsen et al. (2002) calculated the velocity dispersion of  $\sim 1 \text{ km s}^{-1}$  for stars in young clusters and associations. Since the Class I sources are expected to be young ( $\sim 10^5 \text{ yr}$ ), their positions should roughly indicate the place where they have born, whereas with a velocity dispersion of  $1 \text{ km s}^{-1}$ , the Class II YSOs (median age  $\sim 4.5 \times 10^6 \text{ yr}$ ) might have drifted away  $\sim 4 \text{ pc}$  from their original position. Therefore, some of the Class II YSOs distributed away from the cluster center ( $\alpha_{2000} = 07^h 16^m 33^s$ ,  $\delta_{2000} = -09^\circ 25' 35''$ ; see Samal et al. 2007) might have drifted due to their motion. Figure 5 shows the spatial distribution of YSOs. The Class

I source C4 is associated with the structure #2 and is situated at the vertex of a finger-like structure pointing towards the ionization source. A similar kind of example can be seen in the case of RCW 120 (Zavagno et al. 2007; Deharveng et al. 2009), where a YSO located at the vertex of a structure pointing towards the exciting star (Deharveng et al. 2009). Deharveng et al. (2009) proposed that the structure results from the dynamical instability of the expanding ionization front, such as those simulated by Garcia-Segura & Franco (1996). The regions #1 and #3 are associated with Class I sources. The region #1 is associated with a relatively massive ( $\sim 9 M_{\odot}$ ) star and is more prominent in PAH emission in comparison to the region #3, which is associated with a less massive ( $\sim 2.7 M_{\odot}$ ) star. The Class II source 25 seems to be projected near the H<sub>2</sub> structure #4, but its parameters derived from the acceptable SED fitting models suggests that the source is possibly not embedded within the structure.

Though the spatial distribution and evolutionary status of YSOs suggest in favor of triggered star formation, however, with the present data it is not possible to pinpoint the exact nature of triggering, but it is worth discussing the two most likely scenarios that might have happened in this region. In the first case, we discuss the star formation as seen in remnants of pre-existing molecular material of a parental clumpy cloud due to interaction of an expanding H II region. In the second case, we discuss the evolution of an H II region in a filament and the resulting star formation.

In Sh2-294 region, we have identified structures (#1 and #3) with YSO inside and they resembles with the numerical simulation of globules resulted due to the impact of UV photons from the near-by massive OB stars on the pre-existing dense molecular material (Lefloch & Lazareff 1994). The structure #1 shows clearly a externally heated rim, with a massive ( $9 M_{\odot}$ ) source C1 inside the rim, whereas the region #3 has a more globular morphology, with a less massive ( $2.7 M_{\odot}$ ) source C3 inside. In both the cases, the structures show cometary morphology with their heads pointing toward the illuminating B0 MS star. Both the structures are approximately at the same distance from the ionizing source. The different morphological structures under the same set of initial conditions and exposed to approximately the same amount of ionizing photons, may be due to the differences in size and mass of the pre-existing clumps. Several studies show the association of YSOs with bright rims at the borders of H II regions (Sugitani & Ogura 1994; Ogura et al. 2002) and their formation is more likely due to effect of strong external radiation from OB stars (Morgan et al. 2004; Urquhart et al. 2006). On the basis of cometary morphology, location, and age difference between the associated YSOs and the ionization source, one can anticipate that radiation driven implosion (RDI; Lefloch & Lazareff 1994; Miao et al. 2006) could be the process of star formation for regions #1 and #3. To evaluate this hypothesis we quantitatively compare the time elapsed during the formation of the Class I YSO (C1) in the region #1 with that of the age of the B0 ionization source at center. In case of RDI-induced star-formation, the pre-existing molecular clumps are surrounded by high-pressure ionized gas due to the photoionizing UV photons and the pressure exerted on the surface of the molecular clump leads to for-

mation of a cometary globule. At an appropriate time, the high pressure will drive a shock front into the clump, leading to the formation of new stars (for details, see Lefloch & Lazareff 1994). We estimated the time needed for the ionization front (IF) to travel to the present position of the rim of the structure #1 situated at a projected distance of 1.7 pc as  $\sim 1.5 \times 10^5$  yr, assuming that the IF expands at the sound speed of  $11.4 \text{ km s}^{-1}$ . The characteristic timescale for producing cometary morphologies of various shapes and inducing gravitational collapse varies from 0.1 to  $\sim 1 \times 10^6$  yr (Lefloch & Lazareff 1994; Miao et al. 2009), depending upon initial conditions. Hence, we presume an elapsed time to initiate star formation inside the region #1 could be  $\leq 1 \times 10^6$  yr. The age of the Class I source inside the rim should be of the order of  $10^5$  yr. Taken together, the summed time scale ( $\sim 2.6 \times 10^6$  yr) is less than the age ( $\sim 4.0 \times 10^6$  yr) of the ionizing source that powers the H II region. We also evaluated the shock crossing time to the globule to see whether the star formation in regions #1 and #3 started due to the propagation of ionization-shock front or whether it had already taken place prior to the ionization front arrival. Assuming a typical shock velocity of  $1\text{-}2 \text{ km s}^{-1}$ , as found in the case of Bright Rimmed Clouds (BRCs; see e.g., Thompson et al. 2004; White et al. 1999) for the neutral gas associated with #1, the shock travel time to the source C1 projected at a distance  $\sim 0.31$  pc from the photo-ionization surface layer ranges from  $3.0\text{-}1.5 \times 10^5$  yrs. This time scale is comparable to the age of the source C1. These simple approximate estimations suggest that the formation of the source C1 and similarly C3, can be possible via the RDI mechanism.

Now we will discuss the bipolar H II region and its importance on star formation processes. In bipolar case, it is most likely that the H II region forms in the dense region of a filamentary cloud, where the density along the equatorial axis of the filament is high, whereas it is low in the polar directions, leading to a high density contrast. As a consequence, matter can be more compressed in the equatorial plane during the expansion of the H II region, depending upon the initial density and ionization radiation from the H II region. A prototype example of such bipolar morphological H II region is “Sh2-201”, where two dense ( $> 10^{22} \text{ cm}^{-2}$ ) and massive ( $> 70 M_{\odot}$ ) condensations are found at each sides of the waist of Sh2-201 (Deharveng et al. 2012). Sh2-201 is believed to be formed in a large filament that is running east-west of Sh2-201. Massive condensations are the potential sites of new star formation. Indeed, Deharveng et al. (2012) detected two  $100 \mu\text{m}$  point sources possibly of Class 0 nature in the east condensation ( $\sim 235 M_{\odot}$ ) and hypothesized that the triggered star formation is in act at the waist of Sh2-201, which seems to be in accordance with numerical simulations of triggered star formation in a filamentary cloud due to dynamical compression of an expanding H II region (see Fukuda & Hanawa 2000). In the absence of long wavelength observations, it is tempting to guess about the shape and structure of original cloud in which Sh2-294 has formed. However, the morphology of Sh2-294 at  $8 \mu\text{m}$  and  $22 \mu\text{m}$  on a smaller scale suggests that it might be filamentary in nature. Presuming Sh2-294 formed in a filamentary cloud, we compared the observed properties with the numerical simulations.

The numerical simulations by Fukuda & Hanawa (2000), including a wide variety of physical conditions, suggest for typical conditions the H II region takes more than five times the sound crossing time ( $t_{cross}$ : see Eq. (19) of Fukuda & Hanawa 2000), to form the first generation cores (i.e., cores at the waist) in a filament. The first generation cores can be followed by two second generation cores depending on the initial conditions due to the change in self gravity in the filament. The second generation cores in a magnetized cloud are expected to be separated from the first generation cores by the wavelength of most probable fragmentation, which is thirteen times the length scale ( $H$ : see Eq. (18) of Fukuda & Hanawa 2000). The  $t_{cross}$  and  $H$  in the simulations of Fukuda & Hanawa (2000) depend on the sound speed and the central density of the cold filamentary cloud. In Sh2-294, we presume the H<sub>2</sub> structures #1, and #3, situated  $\sim 1.7$  and  $1.8$  pc away from the ionizing source along the long axis seen in  $8 \mu\text{m}$ , perhaps represent the externally heated part of the condensations that are at the waist of Sh2-294. Assuming an effective sound speed  $\sim 0.6 \text{ km s}^{-1}$ , as found in central region of filaments (e.g., Heitsch et al. 2009; the observed velocity dispersion) and the average density  $\sim 10^5\text{-}10^4 \text{ cm}^{-3}$  of the protocluster forming clumps (e.g., Mueller et al. 2002; Motte et al. 2008), as the density of cluster forming filaments, we estimated the length scale and sound crossing time for Sh2-294 as  $\sim 0.04\text{-}0.14$  pc and  $\sim 7.6\text{-}25 \times 10^4$  yr, respectively. The presence of second generation cores cannot be assessed with the present data, but what we see today are certainly the presence of two possible H<sub>2</sub> structures (#1 and #3), with Class I YSOs (C1 and C3) inside of these structures. Assuming that these Class I YSOs are resulted of the cores that might have formed due to the dynamical compression of the expanding H II region as simulated by Fukuda & Hanawa (2000), we calculated the approximate time that might have elapsed in the entire process. In the simulations of Fukuda & Hanawa (2000), the time required to produce dense cores depends upon several factors. We considered those models, which include magnetic field, treat the formation of H II region on the filament axis or very close to it ( $< 5H$ ) as well as impinging the filament axis with a kinetic energy. These models predict the time required to produce two first generation cores ( $\rho > \sqrt{10} \rho_0$ ) is less than or equal to ten times the crossing time scale, which is  $\leq 2.5 \times 10^6$  yr in the present case. The age of the Class I YSOs is of the order of  $\sim 10^5$  yr. Assuming that the age ( $\sim 4 \times 10^6$  yr) of the ionizing source represents the age of H II region, it seems that Sh2-294 is old enough to produce two cores, which perhaps further collapses to form the Class I YSOs.

The above discussion, with the present limited observations suggests that both the hypotheses can be justified being responsible for triggered star formation in Sh2-294 region. It is difficult to conclude with the present observations, which one is superior over the other, though we prefer triggered star formation at the waist of Sh2-294 in a filamentary cloud, as the overall morphology of Sh2-294 on a smaller scale resembles with a filamentary cloud. However, the proof of this would require additional informations such as determination of exact stellar properties of YSOs with infrared spectroscopic observations, a search for in favor of possible filamentary cloud

with deep FIR observations and kinematics with high resolution line observations.

## 5. SUMMARY

In Paper-I we studied the Sh2-294 region and properties of the associated central cluster. With the help of low resolution radio continuum observation at 1280 MHz, mid & far-infrared emissions from MSX & HIREs maps and optical-NIR point source analyses, we tried to understand for the first time, the star formation scenario in the Sh2-294 region. In the present paper the high resolution *Spitzer* images along with H<sub>2</sub> image with VLT reveal the presence of several dusty structures and four prominent H<sub>2</sub> arc-like structures. In this paper we focus on the identification of YSOs and tried to constrain their physical properties using colour-colour selections and SED fitting models. In this study, we identified 25 Class II, 6 Class I and 5 Class I/II sources on the basis of *Spitzer* colours and estimated their basic parameters such as age, mass, disk accretion rate, and extinction using SED fitting models. These parameters provide additional insight into the evolutionary status of these YSOs, thus help us to establish a spatial and temporal correlation among the YSOs and the ionizing source of the Sh2-294. The Class I sources are found to be preferentially situated at the periphery of the H II region and are associated with H<sub>2</sub> arc-like structures. We have also shown that the population of Class I sources is indeed young in comparison to Class II YSO population and B0 MS star at the center of the nebula. The Class I source associated with the structure “#1”, is a massive ( $\sim 9 M_{\odot}$ ) and deeply embedded ( $A_V \sim 24$  mag) protostar, accreting currently with an envelope accretion rate  $\sim 9.8 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ . From the morphology, spatial distribution of YSOs and the time scale involved, we discussed triggered star formation in the region with two possible scenarios. The overall morphology of Sh2-294 along with the time scale involved suggest that the dynamical compression of a filamentary cloud by the expanding H II region, following the simulations of Fukuda & Hanawa (2000), might be the cause for new star formation in the region. However, further observations are needed to confirm this possibility.

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## REFERENCES

- [70] Allen, L. E., Burton, M. G., Ryder, S. D., Ashley, M. C. B., & Storey, J. W. V. 1999, *MNRAS*, 304, 98
- [70] Allen, L. E., Calvet, N., & D'Alessio, P. et al. 2004, *ApJSS*, 154, 363
- [70] Bernasconi, P. A. & Maeder, A. 1996, *A&A*, 307, 829
- [70] Bessell, M. S., & Brett, J. M. 1988, *PASP*, 100, 1134
- [70] Chauhan, N., Ogura, K., Pandey, A. K., Samal, M. R., & Bhatt, B. C., 2011, *PASJ*, 63, 795C.
- [70] Chauhan, N., et al. 2009, *MNRAS*, 396, 964
- [70] Cyganowski, C. J., Whitney, B. A., & Holden, E. et al. 2008, *AJ*, 136, 2391
- [70] Chrysostomou, A., Brand, P. W. J. L., Burton, M. G., & Moorhouse, A. 1992, *MNRAS*, 256, 528
- [70] Churchwell, E., Povich, M. S., & Allen, D. et al. 2006, *ApJ*, 649, 759
- [70] Churchwell, E., Watson, D. F., & Povich, M. S. et al. 2007, *ApJ*, 670, 428
- [70] Cutri, R. M. et al., 2003, *2MASS All Sky Catalog of Point Sources*. Astron. Soc. Pac., San Francisco
- [70] Deharveng, L., Zavagno, A., Caplan, J. 2005, *A&A*, 433, 565
- [70] Deharveng, L., Zavagno, A., & Schuller, F. et al. 2009, *A&A*, 496, 177
- [70] Deharveng, L., Zavagno, A., & Anderson, L. D. et al. 2012, *A&A*, submitted
- [70] Egan, M. P., et al. 2003, *MSX6C Infrared Point Source Catalog (AFRL-VS-TR-2003-1589)*; Bedford: AFCRL)
- [70] Fazio, G. G. et al., 2004a, *ApJS*, 154, 10
- [70] Fazio, G. G. et al. 2004b, *ApJS*, 154, 39
- [70] Flaherty, K. M. et al. 2007, *ApJ*, 663, 1069
- [70] Fukuda, N., & Hanawa, T. 2000, *ApJ*, 533, 911
- [70] Garcia-Segura, G., Franco, J., 1996, *ApJ*, 469, 171
- [70] Giard, M., Bernard, J. P., Lacombe, F., Normand, P., & Rouan, D. 1994, *A&A*, 291, 239
- [70] Hartmann, L., Megeath, S. T., & Allen, L. et al. 2005, *ApJ*, 629, 881
- [70] Heitsch, F., Ballesteros-Paredes, J., & Hartmann, L. 2009, *ApJ*, 704, 1735
- [70] Hillenbrand, L. A., Bauermeister, A., & White, R. J. 2008, 14th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (ASP Conf. Ser. 384), ed. G. van Belle (San Francisco, CA: ASP), 200
- [70] Jose, J., et al. 2008, *MNRAS*, 384, 1675
- [70] Kenyon, S. J., & Hartmann, L. 1995, *ApJS*, 101, 117
- [70] Kenyon, S. J., Hartmann, L. W., Strom, K. M., & Strom, S. E. 1990, *AJ*, 99, 869
- [70] Koenig, X. P., Allen, L. E., Gutermuth, R. A., et al. 2008, *ApJ*, 688, 1142
- [70] Lada, C. J., & Wilking, B. 1984, *ApJ*, 287, 610
- [70] Lada, C. J. 1987, in Peimbert M., Jugaku J., eds, *IAU Symp.* 115, Star Forming Regions. Kluwer, Dordrecht, p. 1
- [70] Lada, C. J. & Lada, E. A. 2003, *ARA&A*, 41, 57
- [70] Lefloch, B., & Lazareff, B. 1994, *A&A*, 289, 559
- [70] Leisawitz, D., Bash, F., & Thaddeus, P. 1989, *ApJS*, 70, 731
- [70] Luhman, K. L., Engelbracht, C. W., & Luhman, M. L. 1998, *ApJ*, 499, 799
- [70] Madsen, S., Dravins, D., & Lindegren, L. 2002, *A&A*, 381, 446
- [70] Meyer, M., Calvet, N., & Hillenbrand, L. A. 1997, *AJ*, 114, 288
- [70] Miao, J., White, G. J., Nelson, R., Thompson, M., & Morgan, L. 2006, *MNRAS*, 369, 143
- [70] Miao, J., White, G. J., Thompson, M. A., & Nelson, R. P. 2009, *ApJ*, 692, 382
- [70] Moffat, A. F. J., Fitzgerald, M., & Jackson, P. D. 1979, *A&ASS*, 38, 197
- [70] Morgan, L. K., Thompson, M. A., Urquhart, J. S., White, G. J., & Miao, J. 2004, *A&A*, 426, 535
- [70] Motte, F., Bontemps, S., Schneider, N., Schilke, P., & Menten, K. M. 2008, *Massive Star Formation: Observations Confront Theory* (ASP Conf. Ser. 387), ed. H. Beuther, H. Linz, & T. Henning (San Francisco, CA: ASP), 22
- [70] Muench, A. A., Lada, C. J., Luhman, K. L., Muzerolle, J., & Young, E. 2007, *AJ*, 134, 411
- [70] Mueller, K. E., Shirley, Y. L., Evans, N. J., II, & Jacobson, H. R. 2002, *ApJS*, 143, 469
- [70] Ogura, K., Sugitani, K., Pickles, A. 2002, *AJ*, 123, 2597
- [70] Ojha, D. K., et al., 2011, *ApJ*, 738, 156
- [70] Pandey, A. K., et al. 2008, *MNRAS*, 383, 1241
- [70] Robitaille, T. P. 2008, *Massive Star Formation: Observations Confront Theory* (ASP Conf. Ser. 387), ed. H. Beuther, H. Linz, & T. Henning (San Francisco, CA: ASP), 290
- [70] Robitaille, T. P., Whitney, B. A., Indebetouw, R., & Wood, K. 2007, *ApJs*, 169, 328
- [70] Robitaille T. P., Whitney B. A., Indebetouw R., Wood K., & Denzmore P. 2006, *ApJS*, 167, 256
- [70] Samal, M. R., et al. 2007, *ApJ*, 671, 555
- [70] Samal, M. R., et al. 2010, *ApJ*, 714, 1015
- [70] Saito, H., et al. 2009, *AJ*, 137, 3149
- [70] Sharma, S., et al. 2007, *MNRAS*, 380, 1141
- [70] Siess, L., Dufour, E., & Forestini, M. 2000, *A&A*, 358, 593
- [70] Sugitani, K., & Ogura, K. 1994, *ApJS*, 92, 163
- [70] Sugitani, K., et al. 2002, *ApJ*, 565, L25
- [70] Thompson, M. A., White, G. J., & Morgan, L. K. et al. 2004, *A&A*, 414, 1017
- [70] Tej, A., Ojha, D. K., Ghosh, S. K. et al. 2006, *A&A*, 452, 203
- [70] Urquhart, J. S., Thompson, M. A., Morgan, L. K., & White, G. J. 2006, *A&A*, 450, 625
- [70] Walter, F. M., & Barry, D. C. 1991, in *The Sun in Time*, ed. C. P. Sonnett et al. (Tucson: Univ. Arizona Press), 633
- [70] Watson, C., Povich, M. S., Churchwell, E. B., et al. 2008, *ApJ*, 681, 1341
- [70] White, G. J., et al. 1999, *A&A*, 342, 233
- [70] Whitney B. A., Wood K., Bjorkman J. E., Cohen M., 2003b, *ApJ*, 598, 1079
- [70] Whitney B. A., Wood K., Bjorkman J. E., Wolff M. J., 2003a, *ApJ*, 591, 1049
- [70] Ybarra, J. E. & Lada, E. A. 2009, *ApJ*, 695, 120
- [70] Yamamura, I. et al. 2009, *ASP Conf. Ser.* 418, *AKARI, a Light to Illuminate the Misty Universe*, ed. T. Onaka et al. (San Francisco, CA: ASP), 3
- [70] Yun J. L., Djupvik A. A., Delgado A. J., Alfaro E. J., 2008, *A&A*, 483, 209
- [70] Wright, E. L., Eisenhardt, P. R. M., & Mainzer, A. K. et al. 2010, *AJ*, 140, 1868
- [70] Zavagno, A., Deharveng, L., Comern, F. et al. 2006, *A&A*, 446, 171
- [70] Zavagno, A., Pomars, M., & Deharveng, L. et al. 2007, *A&A*, 472, 835